Flame Propagation Behaviors in Micron- and Nano-
Titanium Dust Explosions

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ABSTRACT

Particle size has a significant effect on flame propagation behaviors in dust explosions. In this study, the flame propagation behaviors in micron- and nano-titanium dust explosions were observed and compared. Results showed that flame propagation mechanisms in nano- and micron-titanium dust clouds are quite different. Nano-titanium dust flames were characterized by discrete single glowing burning particles with a smooth spherical flame front. Micron-titanium dust flames were marked by clusters of glowing burning particles with an irregular flame front. The nano-titanium flame velocity fluctuated more violently and the average flame propagation velocity was faster than that of the micron-titanium flame. In addition, micro explosion phenomenon occurred significantly in the burning process. SEM photos showed that nano-titanium particles were approximately of spherical shape with observable agglomerations before ignition. However, the combustion products exhibited complicated structures combining the spherical titanium oxides with considerable larger diameters and irregularly spliced smaller titanium oxides. Micron-titanium particles were of irregular shape before ignition, but of spherical shape after combustion. These results indicated that oxidation reactions occurred on the liquid surface of micron- and nano-titanium particles.

KEYWORDS: Dust explosion, titanium particle, flame structure, propagation mechanism.

INTRODUCTION

Accidental dust explosions happen frequently in industrial processes in which combustion metal particles are handled causing great financial losses and people injury. As a metal element of low density, good strength, excellent corrosion resistance and high heat of reaction, titanium is widely used in the industry of spaceflight, spray, metallurgy, fireworks and so on. To take appropriate preventing measures against titanium dust explosion accidents, especially for the ultrafine particles which are more easily ignited [1, 2], the flame propagation mechanisms through combustible metal particle clouds need to be revealed. As particle size has a significant effect on flame propagation behaviors in dust explosions [3], Dobashi and Ju et al. [4, 5] found that the micron-stearic flame structure was determined by the mass density of smaller particles. Gao [6] pointed out that, in the micron scale as the particle size of long-chain monobasic alcohol decreased, reaction kinetics controlled the flame propagation processes in dust explosions. Shafirovich [7] suggested that oxygen diffusion in the gas phase played a major role in the combustion mechanism of 100 μm or larger titanium particles in air, while kinetics became more important for smaller sizes. However, compared with the understanding of micron-dust explosions, the current level of physical understanding of the flame propagation mechanisms in nano-dust explosions is still in a rudimentary state. Considering the agglomeration effect exhibited in nano dust [8], what should the flame propagation behavior expected to be in a nano-dust cloud? In this study, micron- and nano-titanium dust explosion experiments in
open-space were conducted to reveal the combustion behaviors and flame microstructures.

EXPERIMENTS

Experimental apparatus

The experimental apparatus is shown in Fig. 1(a). The combustion system consisted of combustion tubes, a dispersion system, a gas supply system, an ignition source, high-speed photography cameras, and a time controller. The middle combustion tube was designed to move down to create provide an open combustion space so that the flame could propagate in an open field without any influence of the chamber wall. The dispersion system included a gas nozzle, a dispersing cone and a sample container. The gas supply unit consisted of a compressed air bottle, a buffer vessel, a solenoid valve, a pressure reducing valve, two pressure gages and some air pipe lines. The ejected air pressure to disperse the dust particles was 0.5 MPa. The ignition system was composed of a pair of 0.4 mm-diameter tungsten wire electrodes with an ignition gap of about 5 mm and a 15 kV high voltage transformer. Two high-speed cameras (Photron FASTCAM SA 4 and SA 5) with a normal lens (Nikon AF Nikkor 50 mm f/1.2) and a microscopic lens (Nikon AF Micro 200 mm f/4D) were synchronously used to record the flame propagation processes and microstructures. The experimental timing sequence was controlled by a programmable logic controller (OMRON CPM1A). If the start time of the programmable logic controller was set to be 0 s, the timing sequence was as follows: the solenoid valve opened from 0.5 s to 1 s; the electrical stoppers were triggered at 1.2 s and the movable tube was moved down to provide the open combustion space. From 1.4 s, the high speed cameras were started so that the flame propagation behaviors could be recorded completely. At 1.5 s, the transformer was discharged for 0.03 s. The suspended particles was ignited and the flame propagated rapidly in the open space.

Before experiments, the particles were dried in an oven for at least 24 h to reduce the liquid bridge force between the particles caused by water content. The real mass densities of titanium dust clouds was measured by a mass density measurement system modified on the basis of the combustion experimental system, as shown in Fig. 1(b). The measurement system was composed of a particle dispersion unit, a particle capture unit and a particle weigh unit. The particle capture unit was designed to capture the suspended particles in the middle of the tube space. The particle dispersion conditions were the same as the combustion experiments. Results of five repeated experiments proved that the mass densities of 35 μm and 50 nm titanium particles used in comparative experiments were 259.0 g/m$^3$ and 258.5 g/m$^3$.

![Figure 1. Experimental apparatus and mass density measurement system.](image)
Experimental materials

In the experiments, 35 μm and 50 nm titanium powders were chosen as the experimental dusts. Physical-chemical characteristics of titanium particles are presented in Table 1.

<table>
<thead>
<tr>
<th>Name</th>
<th>Titanium</th>
</tr>
</thead>
<tbody>
<tr>
<td>Symbol</td>
<td>Ti</td>
</tr>
<tr>
<td>Standard state</td>
<td>Solid at 298 K</td>
</tr>
<tr>
<td>Relative atomic mass</td>
<td>47.867</td>
</tr>
<tr>
<td>Density of solid (kg/m³)</td>
<td>4507</td>
</tr>
<tr>
<td>Melting point (K)</td>
<td>1941</td>
</tr>
<tr>
<td>Boiling point (K)</td>
<td>3560</td>
</tr>
<tr>
<td>Enthalpy of fusion (kJ/mol)</td>
<td>18.7</td>
</tr>
<tr>
<td>Enthalpy of vaporization (kJ/mol)</td>
<td>425</td>
</tr>
</tbody>
</table>

Before the experiments, thermo-gravitational analysis (TGA) was conducted with a heating rate of 10 K/min to obtain detailed information of thermal weight change of the experimental titanium particles. The thermogravimetric curve and differential thermogravimetric curve are respectively shown in Figs. 2(a)-(b). The data show that, at about 267.5 ℃, the weight of 35 μm titanium particles began to increase gradually due to the oxidation reaction occurring on the particle surface. At about 600 ℃, the rate of weight increase began to increase quickly and then reached its maximum value of 0.1324 mg/℃ at 882.5 ℃. The weight approximately did not change when the temperature went beyond 1000 ℃. On the other hand, the weight of 50 nm titanium particles began to increase gradually at 163 ℃, which meant that the particles began to participate in the oxidation reaction with oxygen. At about 400 ℃, the rate of weight increase became larger and reached the maximum value of 0.0324 mg/℃ at 436 ℃. Due to limitations of the testing apparatus, the maximum temperature was 1100 ℃. When the temperature reached 1100 ℃, the weight of 50 nm titanium particles continued to increase, which indicated that the oxidation reaction of the particles had not finished. The reason of this phenomenon was that heat transfer into the inner particles was delayed due to agglomeration effects, and the oxidation reaction only occurred on the surface of the agglomerates but not inside each particles. It was obviously that the weight increase process of 50 nm titanium particles occurred earlier than that of 35 μm titanium particles and the maximum weight increasing rate of 35 μm titanium particles was considerable larger than that of 50 nm titanium particles. The results demonstrate that 50 nm titanium particles reacted more easily with oxygen compared with 35 μm titanium particles.
Additionally, particle size distributions of 35 μm titanium particles were measured by a Malvern Mastersizer 2000 laser particle size analyzer, and particle size distributions of 50 nm titanium particles were measured by a Malvern Nano-ZS90 laser particle size analyzer. The results are shown in Fig. 3. It is obvious that the size distribution of 35 μm titanium particles was consistent with the value provided by the supplier, and the average particle diameter was 38.1 μm. The size distribution of 50 nm titanium particles gave obviously larger values than that provided due to serious agglomeration effects. The average particle diameter was 360 nm. Despite the presence of the agglomeration effect in 50 nm titanium particles, the average diameter of the 50 nm titanium particles was still much smaller than that of the 35 μm titanium particles. That’s the reason why 50 nm titanium particles reacted more easily with oxygen compared with 35 μm titanium particles in TGA profiles.

![TGA profiles of 35 μm and 50 nm titanium particles.](image)

**Figure 2.** TGA profiles of 35 μm and 50 nm titanium particles.

![Particle size distributions of 35 μm and 50 nm titanium particles.](image)

**Figure 3.** Particle size distributions of 35 μm and 50 nm titanium particles.
RESULTS AND DISCUSSION

Flame propagation behaviors

Flame propagations in 50 nm and 35 μm titanium dust clouds with similar mass density are shown in Fig. 4. The 50 nm titanium dust flame was characterized by discrete single glowing burning particles uniformly distributed in the combustion zone. The flame propagated symmetrically with a smooth spherical flame front. In contrast, the 35 μm titanium dust flame was marked by clusters of glowing burning particles in the combustion zone with an irregular flame front. That was caused by the fact that the turbulence induced by sedimentation and buoyancy of 35 μm titanium particles was more intense than that of 50 nm titanium particles, which caused the non-uniform distribution of unburned particles. No gas phase flame appeared in the combustion process. Oxidation reactions occurred on the surface of the heated solid or liquid titanium particles. The luminous intensity of the 35 μm titanium dust flame was much greater than that of the 50 nm titanium dust flame.

By using digital image processing based on Matlab, the flame edges were extracted. Flame front positions and flame propagation velocities of 50 nm titanium dust cloud with mass density of 258.5 g/m$^3$ and 35 μm titanium dust cloud with mass density of 259.0 g/m$^3$ were obtained as shown in Figs. 5(a)-(b). Results showed that for both micron- and nano-titanium dust clouds, the flame front propagated upward continuously. The flame front of 50 nm titanium dust cloud was faster than that of 35 μm titanium dust cloud after ignition. That was because the 50 nm titanium particles had a larger specific surface area despite the agglomeration effect, which to quicker combustion reaction. The average flame propagation velocities of 50 nm and 35 μm titanium dust clouds were 0.402 m/s and 0.204 m/s, respectively. For both micron- and nano-titanium dust clouds, the flame propagation
velocities fluctuated after ignition. The amplitude of nano-titanium was relatively more intense than that of micron-titanium because 50 nm titanium particles were more sensitive to the influence of turbulence.

![Graphs showing distance from the ignition point and flame propagation velocity over time for different particle sizes.]

**Figure 5.** Flame front positions and flame propagation velocities of 50 nm titanium dust cloud with mass density of 258.5 g/m³ (a) and 35 μm titanium dust cloud with mass density of 259.0 g/m³.

### Flame microstructures and propagation mechanisms

By using high-speed photography with the microscopic lens, the flame microstructures and propagation mechanisms were revealed. As shown in Fig. 6, for 50 nm titanium particles, smaller particles maintained the leading part of the propagating flame. Smaller particles in the flame front first participated in the combustion reaction and heat was released. Subsequently, larger nearby particles absorbed heat and reacted with oxygen to form titanium oxides and emit yellow light. At the same time, smaller particles ahead of these larger particles absorbed heat and were in turn ignited. In this situation, the heat released by the burning smaller particles was sufficient to support the ignition of larger surrounding particles.

![Images showing flame microstructure and propagation mechanism at different times.](image)

**Figure 6.** Flame microstructure (a) and propagation mechanism (b) of 50 nm titanium dust cloud with mass density of 258.5 g/m³.
For the 35 μm titanium particles shown in Fig. 7, the turbulence induced by sedimentation of particles, buoyancy effects, mass transport of oxygen to the burning surface, and heat transfer to the dust particles was more intense than turbulence generated in the case of 50 nm particles, which caused the non-uniform distribution of unburnt particles. In this situation, the flame first propagated towards the smaller particles nearby. Then the larger particles in local high concentration area behind the flame front absorbed enough heat and participated in the combustion reaction to form a cluster of flame. With this cluster of flame developed, the smaller particles in adjacent areas started to burn and released heat. Then the combustion reaction developed to the larger particles behind to form another cluster of flame. Thus clusters of flame that closely connected together formed in quick succession and developed.

**Figure 7.** Flame microstructure (a) and propagation mechanism (b) of 35 μm titanium dust cloud with mass density of 259.0 g/m³.

**Micro explosion phenomenon**

The micro explosion phenomenon occurred in both micron- and nano-titanium particles burning processes as shown in Fig. 8. As the temperature of the titanium particles increased to the ignition point, oxidation reaction occurred on the solid surface and titanium oxides were formed. With the temperature increasing, the titanium particle and the oxides on its surface melted to the liquid phase. Oxygen and nitrogen were absorbed by the surface of the molten titanium oxides due to the Van der Waals’ force. The oxygen was then dissolved by the burning molten titanium through chemical absorption and reacted with the molten titanium. At the same time, the nitrogen dissolved in the burning molten titanium. As the temperature further increased due to the reaction with oxygen, the burning metal became supersaturated with the dissolved gas. Some expanded gases were ejected out of the titanium oxide film, which led to the micro explosions [9, 10]. Micro explosions occurred more intensely during nano-titanium dust flame propagation, which caused clear crackling sounds.

**Figure 8.** Micro explosion phenomenon occurring in micron- and nano-titanium dust flame propagation.
Combustion product analysis

From the scanning electron microscope photographs shown in Fig. 9, it was observed that 35 μm titanium particles were of irregular shape before ignition, but of spherical shape after combustion, which indicated that the oxidation reaction occurred on the liquid phase surface of the titanium particles. The 50 nm titanium particles were approximately spherical in shape with observable agglomerations before ignition. However, the combustion products exhibited complicated structures combined the spherical titanium oxides with considerable larger diameters and irregularly spliced smaller titanium oxides. This result illustrated that the combustion reaction of nano-titanium occurred also in the liquid phase.

**Figure 9.** Scanning electron microscope photographs of 35 μm and 50 nm titanium particles before and after combustion.

CONCLUSIONS

Explosion experiments in unconfined space were conducted with 50 nm and 35 μm titanium dust to reveal the differences of flame propagation behaviors and microstructures. The conclusions obtained were as follows:

1) The 50 nm titanium dust flame was characterized by discrete single glowing burning particles with a smooth spherical flame front. The 35 μm titanium dust flame was marked by clusters of glowing burning particles with an irregular flame front.

2) The flame propagation velocity of the 50 nm titanium dust cloud fluctuated more intensely than that of the 35 μm titanium dust cloud. The average flame propagation velocities of 50 nm and 35 μm titanium dust clouds were 0.402 m/s and 0.204 m/s, respectively.

3) Micro explosions occurred more intensely in nano-titanium dust flame propagation, which caused clear crackling sounds.

4) The 35 μm titanium particles were of irregular shape before ignition, but of spherical shape after combustion. The 50 nm titanium particles were approximately spherical in shape with observable agglomerations before ignition, but the combustion products exhibited complicated structures combining the spherical titanium oxides with considerably larger diameters and irregularly spliced smaller titanium oxides. The oxidation reaction occurred on the liquid phase surface of micron- and nano-titanium particles.
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